Ph.D. Final Synopsis Report

Thesis title

Spectroscopy of the Solar Corona Using Ground and Space-based Observations

Submitted by

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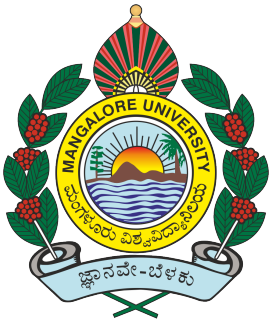

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Title of the Thesis :	**Spectroscopy of the Solar Corona Using Ground and Space-based Observations**
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Final Synopsis report

Abstract

The outer solar atmosphere, the corona, is known for its million-degree temperature. The mystery surrounding the source of this high temperature is gradually being resolved with various theories, observations and models. However, the quest continues and the attempts to understand its detailed dynamics are in progress. Spectroscopy is a widely used technique to study the physical features of astronomical objects. The spectral line profile parameters are obtained and their features are examined. In this project, the coronal spectra from ground-based Fabry-Perot interferometric observations and space-based Hinode/Extreme ultraviolet Imaging Spectrometer (EIS) observations are studied. The various regions of the solar corona like active regions and coronal holes are analyzed. The primary aim is to study the intensity, Doppler velocity, line width and centroid, their inter-dependencies and their spatial and temporal variations.

The Fabry-Perot interferograms were obtained during the total solar eclipse of June 21 2001, observed from Lusaka, Zambia. The duration of the totality was 3 min 37 sec during which 14 interferograms were obtained. EIS is one of the three instruments onboard Hinode which observes the solar corona in the EUV band. The data can be obtained from different regions like the active regions, quiet sun, coronal holes, flares, prominences etc, in different wavelengths. Solarsoft/Interactive Data Language (IDL) is used for the data analysis.

In the analysis using both data, the Doppler velocity and the centroid obtained from the line profiles are mainly emphasized. It is observed that most of the line profiles have multiple components. A line profile is simulated by adding a stationary main component and a varying subsidiary component. The intensity, Doppler velocity and width of the subsidiary component are changed to see how these two parameters affect the resultant Gaussian.

The primary findings from the Fabry-Perot interferograms analysis are the variation of the above-mentioned parameters during the totality and their correlations with the line width and the radial height. The nature of line profiles is studied in detail and it is seen how multiple components introduce asymmetry in them. The EIS spectral data were used to study the coronal active regions spread globally over the Sun for a duration of 13 years. The focus is on the Doppler velocity, centroid and line width, their inter-dependencies and cross-correlations with the solar cycle 24. The study is further extended to the coronal holes as well.

Outline of the Thesis

The primary motive of the thesis is to examine the dynamic nature of the solar corona. In the first chapter, a general introduction to the Sun and solar corona is given with an emphasis on their various physical features and why it is important to study them. In chapter-2, the details of line profile behaviour and how they can be simulated to understand the properties of individual components are briefed. This gives information on the flows and the temperature of the source. The focus is on how the line profile analysis is useful in understanding the physical characteristics of the solar corona. Chapter-3 deals with the Fabry-Perot interferograms obtained from the ground-based observation of a total solar eclipse. The coronal line profiles are analyzed and the results are discussed. In chapter-4, the work on the line profile studies of the coronal active regions using the EIS data is reported. This is followed by chapter-5 on line profile studies of the coronal holes using similar data. The last chapter includes the conclusions and future studies.

Chapter 1: Introduction

This chapter describes the solar properties, its structure and the features of each of its layers. The solar coronal nature and dynamics are included in detail. The present understanding of the solar corona has come a long way. The topics on how one can study the solar corona using total solar eclipses and coronagraphs are elaborated. The early understanding of the corona with primitive instruments and how our understanding has changed gradually are mentioned. This would bring us to our current understanding of the corona and the present-day instruments. Here, the major solar instruments, both ground and space-based, which play a major role in studying our host star are briefed.

Chapter 2: Coronal Spectroscopy & Emission Line Profile Simulations

This thesis deals with the emission line profiles obtained from the solar coronal spectra. The basic principles of coronal spectroscopy and different types of spectrometers are mentioned. The emphasis is mainly on the variation of the Doppler velocity and the centroid of the line profile. It is important to understand how these two parameters are extracted and how they differ from each other. The earlier reports indicate that the majority of the line profiles have multiple components. In order to understand the behaviour of the components, a line profile is simulated by adding a stationary main component and a varying subsidiary component. The intensity, Doppler velocity and width of the subsidiary component are changed to see how these two parameters affect

the resultant line profile. This helps in getting information on the flows and temperature of the solar atmosphere and structures like coronal loops.

Chapter 3: Fabry-Perot Interferometric studies of the Solar Corona in the green line Fe XIV λ5303

This chapter is based on our paper "Characteristics of the Solar Coronal Line Profiles from Fabry-Perot Interferometric Observations" which is published in Solar Physics. Here, the details of Fabry-Perot interferometer, and how it is designed and used to study the solar corona are explained. The circumstances of the total solar eclipse of 21 June 2001 during which the interferograms were taken are given. This is followed by the methodology of calibrating and analyzing the data. Further, the results along with their relevance are reported. A comparison of the results with similar studies is also mentioned. It is concluded by pointing out the need for further studies using space-based data like Hinode/EIS to have a better understanding of the physical parameters mentioned above.

Chapter 4: Studies of the Coronal Active Regions in Fe XII λ195.12 using Hinode/EIS

It is important to study the solar corona in EUV as this is the region in which the coronal emission dominates. Hinode is an ideal instrument for this purpose. The different types of EIS data from various coronal regions are briefed. The data considered includes the coronal active regions starting from the time of the launch of Hinode in October 2006 till 2019, which covers the last two years of solar cycle 23 and solar cycle 24. This chapter is based on our paper "Line Profile Studies of Coronal Active Regions in FeXII λ195.12 Using Hinode/EIS" which is published in The Astrophysical Journal. The data extraction and analysis procedures are reported. Further, the results are discussed which are mainly concerned with the shifts seen in the centroid and the Doppler velocity with respect to the line width. The correlation of the former two parameters with the latter and with the solar cycle are also explained. The results are compared with similar works using EIS and other major space-based data.

Chapter 5: Dynamics of the coronal holes in FeXII λ195.12 using Hinode/EIS

This chapter deals with studies of the coronal holes for a duration of 13 years, covering the last two years of solar cycle 23 and full solar cycle 24. The behaviour of line profile parameters intensity, Doppler velocity, line width and centroid are explained in the coronal holes spread all over the Sun. Various cases on the shifts seen in the centroid and the Doppler velocity with respect to the line width are discussed. A comparison of these results with the different shifts observed in the active regions is also reported.

Chapter 6: Conclusions

This chapter deals with the conclusions of our study. The aim of the thesis is to study the two most important and connected problems in astronomy, namely, solar coronal heating and the acceleration of solar wind. The solar cycle variation of the physical parameters of the solar corona is also studied. Two different emission lines are used in the observations which gives an opportunity to study the solar corona at two different levels. A line profile is simulated by combining a stationary main component and a varying subsidiary component. The intensity, velocity and linewidth of the subsidiary component are varied and the resultant profile is examined. Simulation studies show that the input parameters of the two components affect the resultant profile. The main emphasis of the study is to examine the variation of line profile parameters like intensity, linewidth, non-thermal width, Doppler velocity, asymmetry and line centroid in different coronal regions like the active regions and the coronal holes. The interdependence of the line profile parameters and their variation with the coronal magnetic activity are studied. It has been shown that the coronal line profiles, in general, contain multicomponents. An excess of blueshifts over redshifts is seen in the line profiles. The results give valuable inputs to the understanding of coronal heating, acceleration of solar winds and solar irradiance. The work will be extended by studying other coronal regions like quiet sun, flares, prominences etc. from EIS data. Similar studies can also be carried out with data from other solar space missions like IRIS, SDO, Aditya-L1 etc.

List of Publications

Refereed:

- *Line Profile Studies of Coronal Active Regions in FeXII λ195.12 Using Hinode/EIS*, **Maya Prabhakar** & K.P Raju, 2022, The Astrophysical Journal, Volume 931, 40

  DOI: https://doi.org/10.3847/1538-4357/ac610e

- *Characteristics of the Solar Coronal Line Profiles from Fabry-Perot Interferometric Observations*, **Maya Prabhakar**, K.P Raju & T. Chandrasekhar, 2019, Solar Physics, Volume 294, 26

  DOI: https://doi.org/10.1007/s11207-019-1409-7

Manuscripts in preparation:

- *Dynamics of the coronal holes in FeXII λ195.12 Using Hinode/EIS*, **Maya Prabhakar** & K.P Raju

Conference Proceedings

National:

- 40th Annual Meeting of the Astronomical Society of India(ASI), 25 - 29 March, 2022, Indian Institute of technology, Roorkee, India

  Nature of presentation: **Poster**

  Title: Coronal active regions' line profile studies from Hinode/EIS in Fe XII 195.12Å

  Authors: Maya Prabhakar, K.P Raju

- Young Astronomers Meet,India(ASI) September 24 - 28, 2018, Physical Research Laboratory, Ahmedabad, India

  Nature of presentation: **Poster**

  Title: Fabry-Perot interferometric studies of the solar coronal line profiles

  Authors: Maya Prabhakar, K.P Raju

International:

- Asia Pacific Solar Physics Meeting, 3 - 7 February, 2020, Inter University Center for Astronomy & Astrophysics, Pune, India

  Nature of presentation: **Poster**

  Title: Study of the Physical Properties of the solar corona from EIS/Hinode observations

  Authors: **Maya Prabhakar**, K.P Raju

- Exploring the universe: Near Earth Space Science to Extra Galactic Astronomy, 14 - 17 November, 2018, S. N. Bose National Centre for Basic Sciences, Kolkata, India

  Nature of presentation: **Poster**

  Title: Exploring the inner solar corona through Fabry-Perot interferometric studies

  Authors: **Maya Prabhakar**, K.P Raju

- International Symposiumon on Solar-Terrestrial Physics, 6 - 9 November, 2012, Indian Institute of Science Education and Research, Pune, India

  Nature of presentation: **Poster**

  Title: Analysis of the solar coronal green line profiles from eclipse observations

  Authors: **Maya Prabhakar**, K.P Raju & T. Chandrasekhar

  ASI Conference Series, Vol. 10, pp 137 - 142 Edited by N. Gopalswamy, S. S. Hasan, P. B. Rao and Prasad Subramanian

  https://articles.adsabs.harvard.edu/pdf/2013ASInC..10..137P

Projects carried out in schools & workshops attended

- COSPAR Capacity Building Workshop on Coronal and Interplanetary Shocks: Analysis of Data from Space and Ground Based Instruments, 6 - 17 January 2020, Kodaikanal Solar Observatory, Kodaikanal, India.

  Project description: **"Multiwavelength Studies of Various CME events"**
  This project was carried out under the supervision of Prof. Natchimuthuk Gopalswamy, NASA, Goddard Space Flight Center, where I was taught to analyze CME events and to study the associated radio bursts and their dynamics such as the CME height, the shock height, width and velocity evolution, the Alfven speed and the magnetic field strength. This study held close relevance to my thesis work facilitating me to learn the analysis techniques that can be extended in further studies.

- 5^{th} Indo-French Astronomy School on Spectroscopy and Spectrographs, 16 - 24 August, 2019, Asia Pacific Solar Physics Meeting, 3 - 7 February, 2020, Inter University Center for Astronomy & Astrophysics, Pune, India

  Project description: **Stellar abundances using high-resolution spectra**

  This school helped me in understanding the concepts of spectra, spectroscopy, spectral analysis, classification and applications, integral field spectroscopy, and polarimetry. It emphasized on the participants to work on research projects during the period. I worked on the project entitled "Stellar abundances using high-resolution spectra" under the supervision of Prof. Sunetra Giridhar, Indian Institute of Astrophysics. Here I learnt calculating the radial velocity of sample stars by line identification method using IRAF. Further, the radial velocity was determined using cross-correlation method on IRAF. A sample star whose spectra was wavelength calibrated and continuum normalized was given and the atmospheric parameters of effective temperature, surface gravity and microturbulence velocity was determined using Kurucz model or using MOOG and Supermongo. The abundances of various elements was determined. This project facilitated me in understanding the determination techniques of stellar abundances which can be further extended for several astronomical objects.

- Solar Physics Summer School, 10 - 16 June, 2019, Raman Research Center, Leh India

  Project description: This school was useful with lectures on di ff ere nt topics from Solar interior: Dynamo theory, MHD waves and coronal seismology, Solar magnetism and the structure and dynamics of the solar atmosphere, Solar flares, Coronal heating, Solar activity: coronal mass

ejections, Solar Prominences, Solar wind and heliosphere, Solar variability over large time scale and space climate. It also introduced me to NLST and Adithya-L1 projects

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Mangalagangotri
March 2023

Maya Prabhakar (Ph.D. Student, IIA)

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